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Offshore Earthquake Geotechnology — First Part

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SYNOPSIS This first part of the paper outlines the problems encountered offshore compared to onshore. The most important difference is the presence of water which changes the dynamic behaviour of structures, introduces new forces, complicates the soil investigation and visual site inspection, and changes the characteristics of the earthquake ground motion. Furthermore, the structures offshore may be much larger than most onshore facilitites, and other environmental loads may act simultaneously with an earthquake.

INTRODUCTION

Several excellent state-of-the-art papers have recently dealt with the topics contained within the broad scope of this title. To the writer's knowledge, however, this is the first time offshore earthquake geotechnology is treated specifically, and this presentation, therefore, attempts to give a general outline of the problems encountered offshore compared to onshore, together with an overview of analytical and design procedures applicable for offshore use. This first part of the paper presents an overview of the problems; the second part, to be presented in the last volume of conference proceedings, will discuss design and analytical procedures in more detail.

Due to the writer's background, much of the discussion will be related to gravity structures and North Sea conditions.

COMPARISON OF OFFSHORE AND ONSHORE GEOTECHNOLOGY

The task of the engineer in earthquake geotechnology is to

- evaluate effects of local geology and soil conditions on the characteristics of earthquake ground shaking;
- evaluate effects of earthquake ground shaking on stability and deformations of soil deposits;
- ensure safe and economic aseismic design of soil foundations and soil structures;
- evaluate dynamic characteristics of soil foundations for use in structural design.

These tasks are the same offshore as onshore. The geotechnical engineer working offshore draws heavily from the knowledge and experience obtained onshore, for instance in the design of nuclear power plants. Offshore problems are, however, in many respects different from those encountered onshore, and experience may not be directly transferable. Specific examples of these differences include :

(1) The structures offshore are often much larger than most onshore facilitites, (2) other environmental forces may act simultaneously with the earthquake, see Fig. 1; and (3) the presence of water changes the dynamic behaviour of structures, changes the characteristics of the earthquake ground motion and introduces new forces.

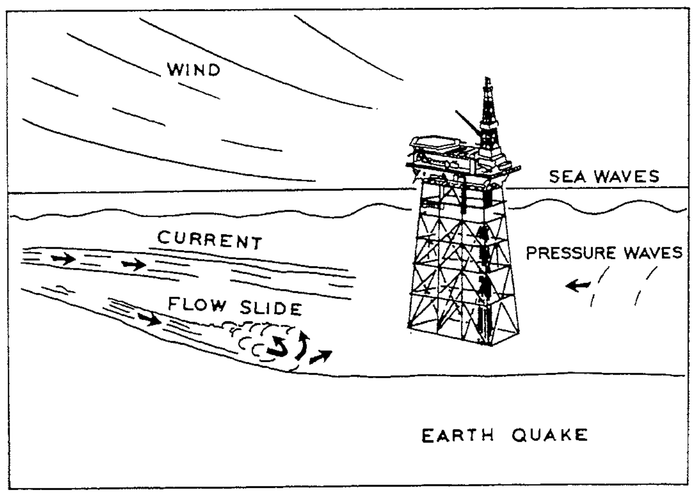

Fig. 1 Environmental forces on offshore structures

Another major difference involves the travel distance of flowslides. Flowslides triggered by an earthquake may propagate for considerably longer distances in water than in air; distance of more than 100 km in gently sloping ground have been reported (Moore, 1978). Earthquakes furthermore generate pressure waves in the water. That they can be quite noticable is testified by this excerpt from a newspaper article describing the situation in Oslo harbour during an earthquake in 1904 :

"The water erupted all over, as if it had started to boil, and on board ships it felt like violent heavy seas. Simultaneously, hard blows seemed to hit against the ship's hull. Many ships already speeding on course came to a full stop, such that the crew believed that they had suddenly run ashore".

This earthquake was of magnitude 6 - 6.5, and the zone of main energy release was 70 - 80 km away from the harbour (Selnes et al., 1980).

It may be of some interest to list characteristics of the geotechnical problems encountered for fixed offshore oil and gas structures. Since many of the methods used offshore are based on advanced procedures developed for nuclear power plants, the characteristics of such structures are also listed for comparison.

Offshore oil gravity structure	Nuclear power plant
- Built where the hydrocarbons are found, very weak foundations may have to be utilized.	- Favourable site conditions selected.
- Surface or shallow foundation.	- Embedded foundation.
- Frequency of interest > 0.2 Hz.	- Frequency of interest > 1 Hz.
- Base width up to 150 m, out-of-phase motion may be important.	- Base width generally less than 60 m.
- Sea-waves, current, wind; simultaneous action with earthquake possible.	- Other environmental forces negligible.
- Design may be for collapse loads, Analysis of permanent and cyclic displacements desired.	- Design does not allow significant plastic yielding to occur - i.e. equivalent linear analysis and superposition methods are applicable.
- Surrounding water gives added mass and damping to the structure, complicates soil investigation and visual site inspection, transmits P-waves and increases travel distance of flowslides.	- No water above the ground.
- Relatively high degree of sample disturbance, in situ testing limited.	- High quality sampling and in situ tests possible.
- High erosion, high amount of superficial material transport.	- No erosion.

Vertical accelerations are more important offshore than onshore. Static design onshore corresponds to gravity loading while offshore structures are designed for submerged weight only. The vertical earthquake forces on the other hand, are proportional to the mass of the structure onshore and to the mass of the structure plus added mass from water onshore.

Soil investigations offshore are, in general, carried out to a much smaller extent than for equally important structures onshore. The sample quality is furthermore rarely as good as onshore due to high water pressure (high total in situ pressure), insufficient heave compensation during sampling,and unsophisticated sampling techniques. Accordingly, methods to correct for sample disturbance become very important offshore (Lee (1979),Andresen et al. (1979), Schjetne and Brylawski (1979), Wood (1979), Høeg (1980)).

While sample disturbance may result in conservative design for foundation stability, the design of the superstructure may be on the unsafe side since a stiffer foundation in general yields higher stresses in the structure for earthquake loading.

The soils encountered offshore vary greatly and include very soft and loose materials. Both deposition and erosion occur at a much more rapid rate than onshore, and mobile superficial deposits may represent a problem. Rapid deposition may also lead to the presence of underconsolidated materials.

Pockmarks and gasified sediments have also often been found in connection with offshore oil fields.

CODES OF PRACTICE

Three codes, the API (1977), ACI (1978), and DnV (1977) deal with earthquake design of fixed offshore platforms. In addition, Ozaki and Hayashi (1978) describe a proposal for a Japanese offshore earthquake design code. Some other codes also contain information of interest, notably the ATC (1978) code for seismic design of onshore structures and the FIP (1977) code for design of prestressed concrete structures. FIP is presently working on seismic design requirements.

The offshore codes seem to be mainly concerned with structural design, and contain relatively little detail about geotechnical requirements. Recommendations concerning soils and foundations are summarized below :

. Effects of local soil conditions on earthquake ground motions should be evaluated (all codes). Response spectral values are given for rock and various soil conditions in the API and ATC codes and in the Japanese proposal.

. Effects of soil-water-structure interaction should be considered (all offshore codes). The soil-structure interaction analysis should account for the variation of soil properties with depth below mudline and give appropriate consideration to the nonlinear behaviour of the soil (ACI).

. The stability of the sea floor should be investigated including effects of the structure, possible future structures, wave loads and earthquakes (ACI).

. Effects of repeated shear stress applications should be accounted for in the design (ACI).

. Characteristic properties of the soil should be taken as conservative mean estimates (DnV). Partial safety factors of 1.4 and 1.2 should be used on the cohesive and frictional part of the soil strength, respectively (ACI).

. When the foundation dimensions exceed 100 m, careful consideration should be given to the phase difference of the earthquake ground motion (Japanese proposal).

OFFSHORE STRUCTURES

Offshore structures presently in use or in the advanced planning stages are oil drilling, production and storage platforms, LNG terminals, mooring bouys, and pipelines. These may be pile-supported or gravity founded, or compliant and floating structures with pile or gravity anchors. Major construction activities and structures are shown on Fig. 2, and various deep sea platform concepts are shown on Fig.3.

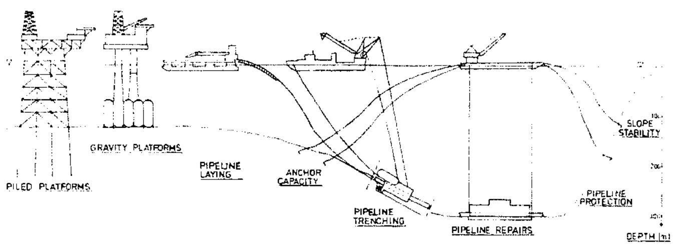

Fig. 2 Major construction activities in the North Sea (Andresen et al., 1979)

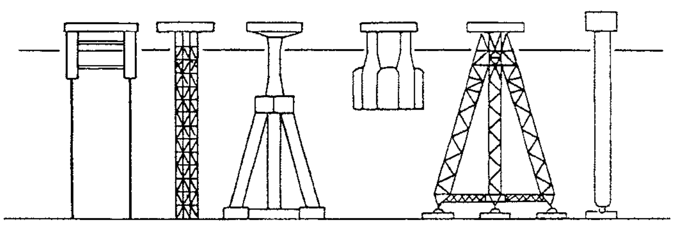

Fig. 3 Platform concepts for deep waters.

Two typical offshore gravity structures are shown on Fig. 4. The gravity structures installed so far in the North Sea have foundation areas ranging from 5500 to 15000 m^2 and submerged weights of 1.6 to 3.2 x 10^6 kN. Total mass including added mass from water may be up to 1.5 x 10^6 ton. The structure to the left in Fig. 4 has a flat bottom while the structure on the right has a bottom consisting of domes with steel skirts extending 4 m below the ground, dowels extending 5 m below the skirts, and anti-liquefaction wells penetrating to a depth of 20-30 m to keep a permanent pore water underpressure of 10 - 20 m.

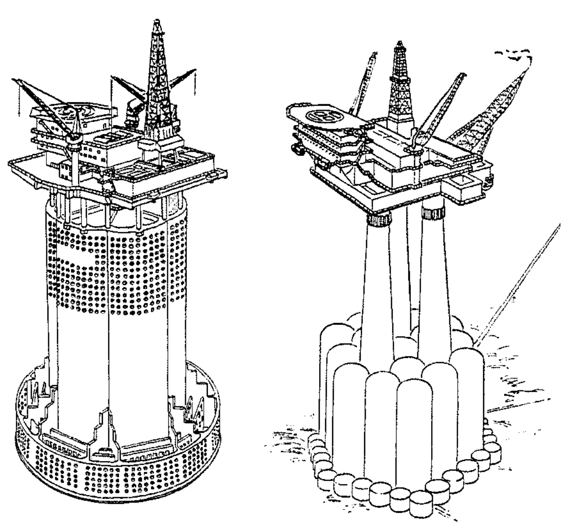

Fig. 4 Condeep and Doris type concrete gravity platforms (from FIP, 1978).

Gravity structures allow most of the construction to be finished in sheltered water before they are towed out to the site. They also have considerable capacity for storage of hydrocarbons. Large mass, low center of gravity and large foundation dimensions characterize these structures, Eide et al. (1979), Chapman (1979), Høeg (1980).

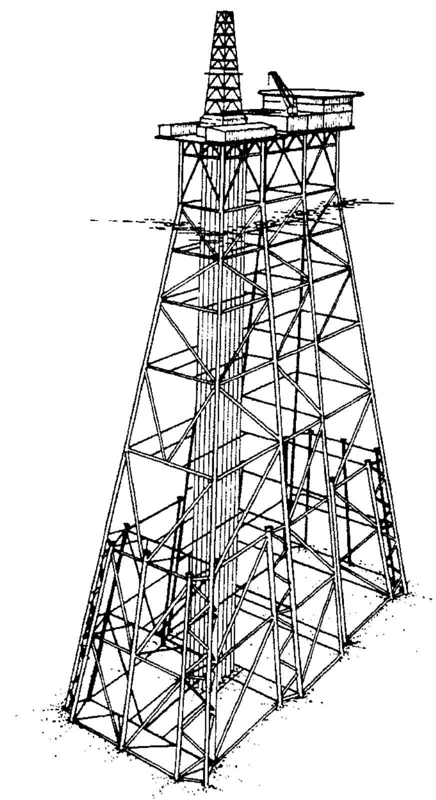

Fig. 5 A pile supported steel template platform (Nair, 1978).

A typical steel jacket structure is shown on Fig. 5. This is by far the most common kind of offshore structure which consists of a deck with equipment supported by a jacket again supported by piles. The piles are driven through the jacket legs and additional skirt piles are braced into the lower part of the structure. Pile diameters may be 1 to 2 m. (Høeg (1980), Chapman (1979), de Ruiter & Beringen (1979)).

Offshore pipelines are used for transport of hydrocarbons. The trenching for the pipelines has up to the present been carried out from surface vessels. The embedments obtained by such operations have not all been equally successful, and offshore pipelines may for considerable lengths have no or only small embedment. After installation one may find sections with free spaces up to 30 - 50 m. Embedded sections have usually backfill of very loose material.

Mooring buoys are used for transfer of hydrocarbons to ships. These structures have very long fundamental periods, and the universal joint is a critical part of the design.

In the not too distant future the geotechnical engineer may also face new challenges from the design and construction of artificial islands, thermopower- and wave power plants, and offshore mining facilities.

EARTHQUAKES

Earthquakes are caused by the sudden release of energy from a fault or a fault complex. The stresses in a region build up slowly due to tectonic movement, and the release of these stresses will occur along old planes of weakness (faults) whenever the stresses at anyone point becomes greater than the failure strength. Release of stresses at one point increases the stresses nearby, and the fault rupture may propagate for several hundred kilometers.

The release of energy per unit of time and area is mainly a function of source mechanism and seismic region. Stress release over a larger area will release more energy and waves from different parts of the fault may superimpose. Larger earthquakes will, therefore, in general cause larger maximum acceleration (or velocity or displacement), energy distributed over a larger range of frequencies, and longer duration, than smaller ones.

Maximum Acceleration Relations

A very wide selection of relations between magnitude, maximum acceleration, and distance is available. For strong motions near the source, relations using epicentral distance should not be used. The reason for this, as discussed above, is that energy is generated along the whole fault rupture; the epicenter is only the projection to the surface of the initiation point of the rupture, i.e. the weak point on the fault where the rupture started.

Seed et al. (1975) presents relations between maximum acceleration, and distance for different types of soil conditions. Idriss (1979) presents attenuation relations for various seismic regions and maximum near-source acceleration values. A semi-empirical method for taking into account fault size, depth and wave transmission characteristics of the base rock was proposed by Schnabel and Seed (1979).

Earthquakes occurring within the plates (intraplate) seem to generate motions with higher frequency and higher acceleration than earthquakes occurring at the plate boundaries (interplate) (Kanamori and Anderson, 1975). Almost all our strong motion data are from interplate earthquakes.

Frequency Distribution of Energy

The frequency distribution of energy is a function of fault mechanism, seismic region, earthquake size, local geology and soil conditions.

Seed et al. (1974) presented average response spectral values for various types of soil. While fault mechanism and seismic region clearly also affect the frequency distribution, these effects are less well understood.

Hydrocarbons are found in sedimentary rock deposits. Structures connected with oil or gas developments will therefore invariably be sited on thick sedimentary rock covers. This may well enchance the long period motion of earthquakes (Swanger and Boore, 1978).

Traveling Waves

The traveling wave problem, i.e. the component of the earthquake motion with horizontal travel path, increases in importance with increase in foundation size. It is desirable to differentiate between two types of traveling waves, i.e. waves traveling in the upper soil layers and waves traveling along the base rock. The soil surface waves are usually not important since strong motions traveling in soil will attenuate rapidly (Seed and Lysmer (1980), Udaka et al. (1979)). Studies indicating significant energy in soil surface waves have mostly been for intermediate and large source distances.

Surface waves traveling along the base rock can be analysed by any of the available methods based on the vertically propagating wave consept; however, the motions will be out-of-phase in the horizontal plane. Such out-of-phase motion will suppress the higher frequencies transmitted to the structure and cause lateral strains in the foundations. This will also lead to large stresses in pipelines.

Vertical Earthquake Component

The presence of water changes the characteristics of the vertical component of the ground motion since water transmits pressure waves. The effect of a layer of water is a function of the water depth and of the impedance ratio between the water and the top soil layer.

OTHER ENVIRONMENTAL LOADS

For regions with relatively low seismic activity, sea waves will in general cause the higher loads on the structure. Earthquake forces may, however, still be important. Forces in a steel jacket structure computed for 100-year design forces from earthquake and sea waves are shown in Table I for a region outside the west coast of Norway, Selnes et al. (1980).

Location	Sea-wave +current +wind	Seismic	
		Stiff soil	Medium stiff soil
Deck support	1.0	1.4	1.2
Piles	1.0	0.45	0.5

Table I. Normalized horizontal shear for 100-year environmental loading. The seismic load is 0.1g maximum acceleration (Selnes et al., 1980).

Earthquake and sea wave 100-year design forces were 0.1 g maximum acceleration and 31 m trough to crest height, respectively. Even for a such relatively low earthquake load, the forces on the structure from the earthquake are comparable to those from the sea wave.

For more seismic regions, earthquake forces may govern the design. On soft foundations where the earthquake loading may stress the soil to near failure, even a relatively small additional load, from sea waves, wind or current may cause a significant increase in displacements, both cyclic and permanent.

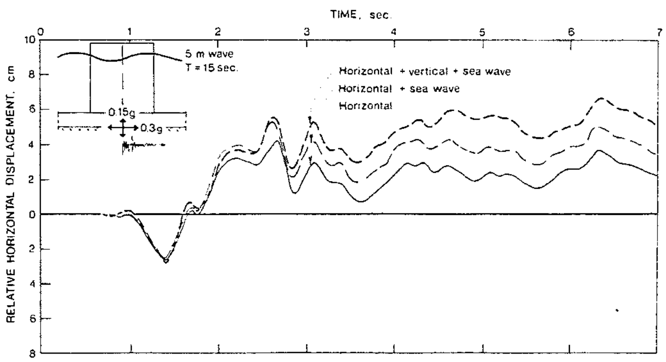

Fig. 6 Horizontal displacements computed for earthquake and sea wave loading (Selnes, 1980).

An example of simultaneous loading is shown in Fig. 6. Computations showed that a 5-m sea wave acting together with the horizontal component of an earthquake gave an increase of some 40% over the displacements from the earthquake alone.

The maximum forces on a gravity structure from a 31 m wave are shown on Fig. 7. The period of motion is generally within 5 - 20 sec. for larger waves, and the energy is concentrated in a very narrow band. Wind forces are relatively small and may be only 10 - 20% of the forces from the sea wave. Sea current forces are also usually relatively minor.

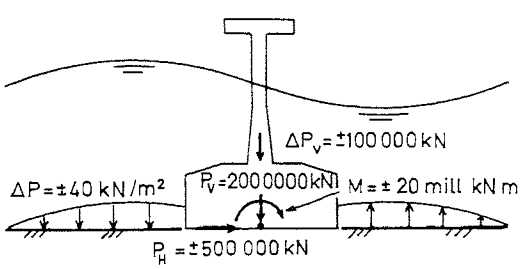

Fig. 7 Forces on a gravity structure from the 100-year design sea wave (Schjetne et al., 1979).

ANALYSES

The selèction of method of analysis must be based on the level of strain developed in the soil during the earthquake. While linear elastic analyses of soil behaviour may be acceptable provided the level of strain is low enough, nonlinear effects become very important at higher strain and must be taken into account.

Nonlinear effects and the required increase in degree of sophistication in the analytical modelling of the soil with increase in strain are illustrated in Fig. 8.

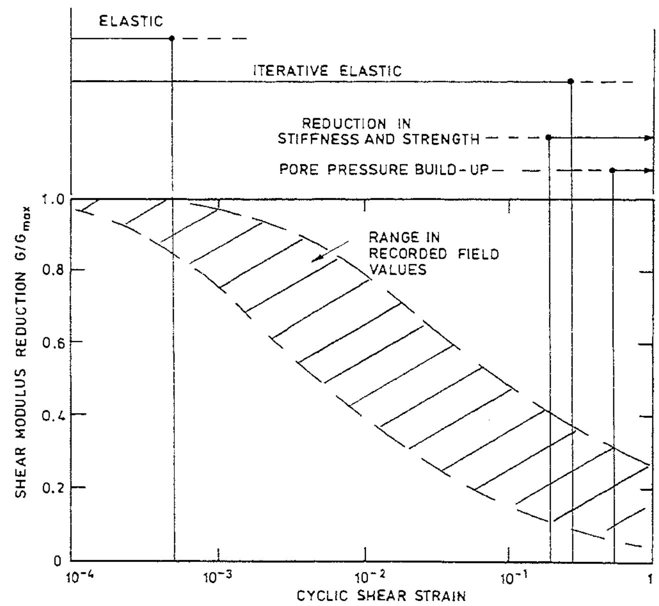

Fig. 8 Nonlinear effects and methods of analyses for various strain levels. Recorded field values are from Arango et al., (1978).

Low-Strain Analyses

For levels of loading where the soil strains remain below about 0.1 - 0.5 percent, most linear elastic methods of analyses may be applied by adapting some iterative scheme to obtain soil properties compatible with the strains (equivalent linear procedures, Seed and Idriss, (1969)). Superposition methods are applicable in this range. The state-of-the-art for such analyses is well advanced, and the engineer can choose from a number of procedures; from simple response spectrum analyses to axisymmetric, approximate three-dimensional and advanced soil-pile-structure interaction analyses. True three-dimensional analyses are also well underway.

The reliability of these procedures has to some extent been verified against observed performance. Deformations and stability are usually not of any concern when strains are below this range. The main geotechnical task will be to give the structural engineer the necessary data about dynamic foundation characteristics for use in the structural design.

The use of free-field properties beneath the foundation is more likely to be a sufficiently accurate approximation for low levels of strain. As seen from Fig. 8, a change in strain by a factor of 10 changes the stiffness by less than a factor of 2 as long as the strains are below 0.05 - 0.1 percent. It must be kept in mind, however, that the change in stiffness due to a change in strain level will be higher in iterative analyses than indicated in the figure due to the cumulative effects of stiffness reduction - lower stiffness leads to higher strains which in turn give lower stiffness. Also, many offshore structures are larger and have considerably higher mass than onshore structures, thus soil-structure interaction effects are likely to be more important.

High-Strain Analyses

For levels of loading where the soil strains exceed about 0.1 - 0.5 percent, the status of available analytical procedures is not equally well founded. One-dimensional procedures are available which take into account several nonlinear effects, and there are also approximate nonlinear two-and-three-dimensional methods usually based on nonlinear spring-dashpot systems. Another approach in present use is to evaluate various effects in separate analyses.

There is, however, at present no generally accepted method for two-dimensional nonlinear dynamic analyses, not to mention three-dimensional, which incorporates realistic large strain soil behaviour such as reduction in stiffness and strength with time, pore pressure build-up or volume change, strain increment direction different from stress increment direction, and strain rate effect on stiffness and strength.

Non-linear soil-structure analyses which take such effects into account are desirable for structures on weak foundations and for strong earthquake motions. For cases where computed soil strains from iterative elastic methods exceed about 0.1 - 0.5 percent, stability and displacements begin to be of concern, and foundation performance should be evaluated in terms of cyclic and permanent displacements.

In other words, when iterative elastic procedures give strains less than about 0.1 - 0.5 percent, we know that the analysis is reasonably accurate, that the foundation will be stable, and that displacements will be small. When strains computed by iterative elastic procedures are above about 0.1 - 0.5 percent, all we know is that our method of analysis is not really applicable to the problem, that displacements may begin to be of concern, that pore pressure may begin to build up significantly, that stiffness and strength probably will detoriate, and that the displacements probably will be in a direction different from the cyclic load direction.

Several nonlinear analyses with various degrees of simplifying assumptions have given relatively small and quite tolerable foundation movements even for earthquake effects producing soil stresses well into the failure range, (Watt et al. (1978), Selnes (1980), Kausel et al. (1970)). If this is the true behaviour of offshore structures, the necessary ductility to take large earthquake forces can be provided by the foundation, thus reducing the forces on the structure. Such a "soft first floor" design may prove to be more easily adapted offshore than onshore. There is, however, still a long way to go before nonlinear analytical tools are developed and verified to an extent that allow such design concepts to be fully utilized.

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